In-Situ Wave Observations in the High Resolution Air-Sea Interaction DRI

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Award Number: N0001408WR201076
http://www.oc.nps.navy.mil/wavelab/

LONG-TERM GOALS

Ocean wave prediction models, based on a spectral energy balance, are widely used to obtain wind-wave forecasts and hindcasts on global and regional scales (e.g., Komen et al., 1994). However, these inherently stochastic models assume a Gaussian and homogeneous sea state and thus do not describe the nonlinear instability processes that can dramatically alter the structure of wave groups and produce anomalously large waves, also known as 'freak' or 'rogue' waves (e.g., Janssen, 2003). Fully deterministic modeling capabilities are now becoming available that incorporate these nonlinear effects and provide the detailed phase-resolved sea surface predictions needed in many applications. Concurrent with the development of new models, advances in radar remote sensing techniques are enabling the detailed observation of the sea surface on the scales of wave groups and individual waves. The long-term goal of this research is to test these emerging new models and measurement technologies in realistic sea states and use them to better understand and predict the wave group structure and occurrence of extreme waves in the ocean.

OBJECTIVES

- Observe the nonlinear evolution of wave groups in realistic broad-band sea states.
- Provide ground-truth data for testing the capabilities of ship-board wave radar systems.
- Provide in-situ wave data for the verification of phase-resolving wave prediction models.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
In-Situ Wave Observations In The High Resolution Air-Sea Interaction DRI

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School,Department of Oceanography, Code OC/He,Monterey,CA,93943

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
Ocean wave prediction models, based on a spectral energy balance, are widely used to obtain windwave forecasts and hindcasts on global and regional scales (e.g., Komen et al., 1994). However, these inherently stochastic models assume a Gaussian and homogeneous sea state and thus do not describe the nonlinear instability processes that can dramatically alter the structure of wave groups and produce anomalously large waves, also known as ?freak? or ?rogue? waves (e.g., Janssen, 2003). Fully deterministic modeling capabilities are now becoming available that incorporate these nonlinear effects and provide the detailed phase-resolved sea surface predictions needed in many applications. Concurrent with the development of new models, advances in radar remote sensing techniques are enabling the detailed observation of the sea surface on the scales of wave groups and individual waves. The long-term goal of this research is to test these emerging new models and measurement technologies in realistic sea states and use them to better understand and predict the wave group structure and occurrence of extreme waves in the ocean.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

The primary goal of the High Resolution Air-Sea Interaction DRI is to advance observational and modeling techniques for monitoring the wave-resolved sea surface around a vessel. Field experiments will be conducted off the California coast, using the floating platform FLIP with a suite of meteorological and oceanographic instruments, airborne and ship-board radar systems, and an array of moored and free drifting buoys. Our proposed contribution to these experiments is an array of surface-following buoys that will be embedded within the footprints of FLIP-based, airborne and ship-board remote sensing systems. The array will cover a nominal area of about 15 by 15 km that spans the anticipated evolution scales of nonlinear wave groups.

The Datawell Directional Waverider (DWR) buoys that will be used in the experiments, are small surface-following buoys that measure vertical and horizontal water particle motion at the sea surface directly, from which time series of surface height and slopes can be extracted. The accuracy of these buoys is well established (e.g., O'Reilly et al., 1996) and their reliability in high sea states is attractive for long-term deployments in the open ocean. We have successfully used DWR buoys in the recent ONR-sponsored SHOWEX (Ardhuin et al., 2003; 2007) and NCEX (Magne et al., 2006) experiments and believe they are well suited to conduct the proposed measurements in an energetic wave environment. To accommodate both high spatial resolution and flexibility in the array design and sampling scheme, we plan to use a combination of moored and free-floating DWR buoys. The larger (0.7 or 0.9 m diameter) DWR buoys will be moored within a few km of FLIP to obtain continuous in-situ surface wave measurements within the footprint of FLIP-mounted radar and other remote sensing systems. The smaller (0.4 m diameter) mini-DWR buoys will be deployed during the intensive phases of the experiments when ship-board radar measurements and aircraft over-flights take place. These buoys are free floating and can be deployed from the same vessel that collects the radar measurements, thus allowing for close coordination of the sampling schemes.

To optimize array design for observing wave group evolution, we will use a forward-scattering angular-spectrum model [see e.g. Dalrymple & Kirby, 1988; Janssen et al. 2006]. This model presumes waves to propagate in a half plane, thus omitting back-scattered wave energy, or waves traveling at a larger than 90 degree angle with respect to the principal direction; it accounts for cubic nonlinearity that is believed to be the primary mechanism for nonlinear wave group evolution in deep water and the associated development of freak waves (Janssen, 2003). In Figure 1 we show two simulations with the angular-spectrum model to illustrate the group-length scales and characteristics anticipated off the California coast where the experiments will take place. We initialize the model utilizing observed frequency-directional spectra extracted from the Coastal Data Information Program (CDIP) Harvest buoy located in 204 m depth off Point Conception. The initial sea surface is assumed Gaussian and homogeneous, with spectral amplitudes and phases selected from a Rayleigh and uniform distribution respectively. The model evolves these spectral components, while allowing for cubic nonlinear coupling; other nonlinear physics (e.g. atmospheric forcing and whitecapping) are not included in these simulations.

The simulations (Figure 1) include examples of typical summer and winter conditions. The summer-time example shows a long-period swell arriving from the South and a weaker high-frequency local wind sea from the North-West. The long propagation distance of the swell

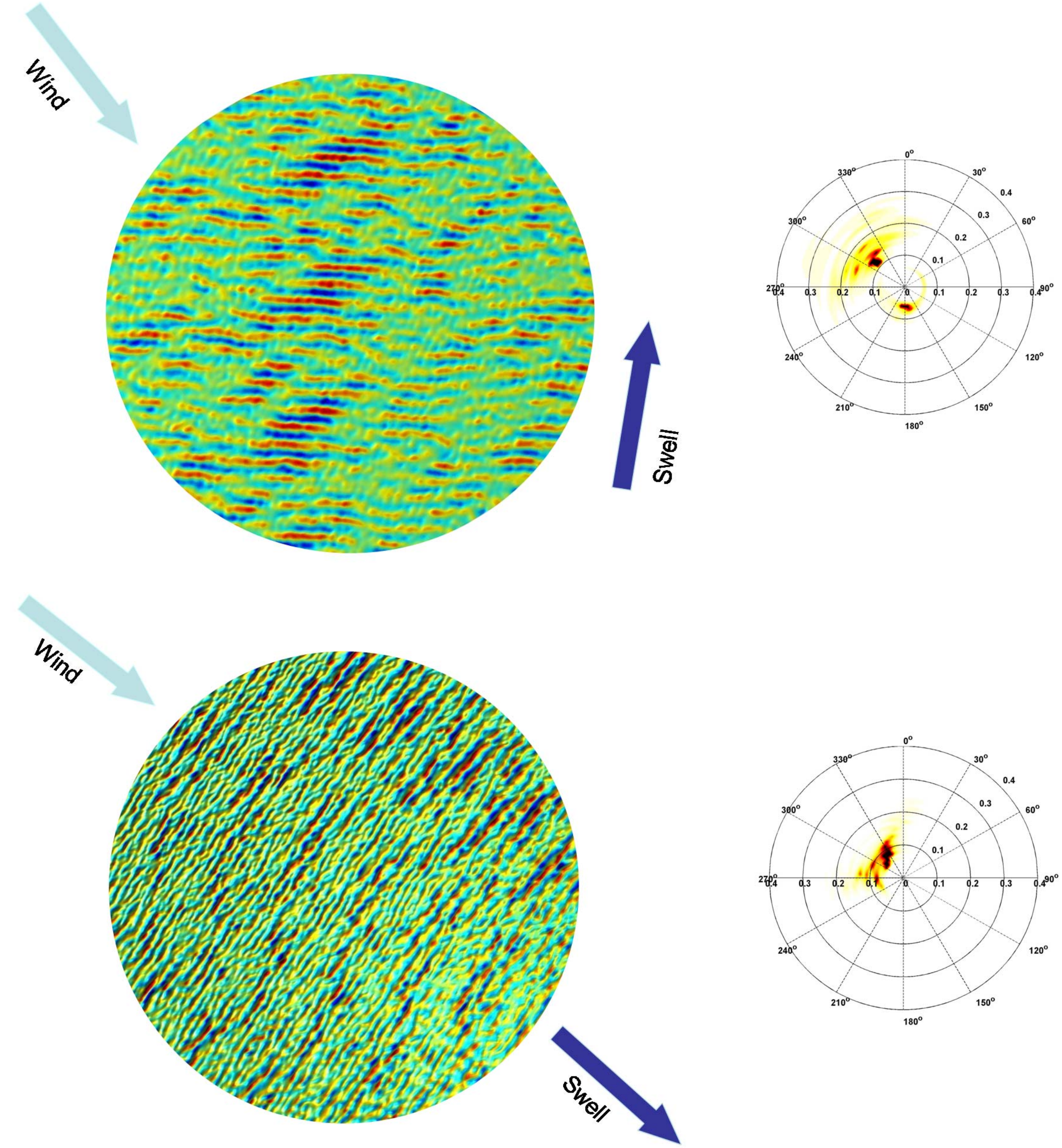

Figure 1. Simulation of sea surface based on buoy observations at Harvest Platform located in deep water off Point Conception, CA. Left panels: snapshot (diameter about 12 km) of simulated sea surface elevation. Right panels: corresponding observed frequency-directional wave spectra (source: CDIP). Upper panels: Typical summer-time South swell in the presence of a light North-West wind sea. Observations were taken in June 2006 (significant wave height 1 m, peak period 17 s). Lower panels: energetic North-West swells and sea in December 2006 (significant wave height 9 m, peak period 14 s).

originating from the Southern hemisphere is evident in the narrow spectrum and long crest lengths (several km). The groups of 6-8 waves are fairly regular at intervals of about 3-4 km. In contrast, the lower panels of Figure 1 show an energetic winter storm event with strong winds and swell arriving from the North-West. This less dispersed wave field (i.e. closer to the generation source) has a broader spectrum and a more irregular group structure.

The tentative experiment plan, described below uses nominally 5 buoys spanning a distance of 10-20 km that includes several wave groups. These measurements, together with other in-situ instruments deployed by other investigators (i.e. sensors mounted on FLIP) and remote sensing observations (ship-board and airborne radars) will allow for a detailed investigation of nonlinear wave evolution over scales of a few wavelengths to several wave groups.

WORK COMPLETED

During FY08 we participated in the continued planning of the High Resolution Air-Sea Interaction DRI. During several meetings at the Scripps Institution of Oceanography a plan was developed for the main three-year phase of the DRI (FY08-FY10). The field experiments will be conducted in two stages: a pilot experiment in the spring of 2009 followed by the main experiment in the spring of 2010. Both experiments are tentatively planned to take place off the California coast in about 500 m depth.

In the pilot experiment we tentatively plan to deploy one moored DWR buoy and two free-floating mini-DWR buoys. Other DRI participants will collect ship-board and airborne radar observations of the surface wave field, video observations of wave breaking events, and various atmospheric measurements.

The pilot experiment will span approximately a 7-day period to allow for acquisition of a data set with a range of conditions that will be useful for initializing numerical models. Our main goals are to try out different buoy deployment strategies to optimize their use in the main experiment, and test the precise synchronization in time and space with other experiment components to achieve a fully integrated data set. The pilot experiment will also provide us with a data set for preliminary analysis of nonlinear wave group evolution physics that will be used to improve the design of the main experiment.

In the main experiment, centered around the Scripps platform FLIP in about 500 m depth, we plan to deploy a more extensive array of DWR buoys spanning an area of about 10-20 km that contains the footprints of FLIP-based and shipboard radar systems (Figure 2). We will deploy three moored, DWR buoys to provide continuous in-situ wave observations during the experiment for validation of radar processing schemes in a wide range of conditions. In addition, we will deploy several free-floating mini-DWR buoys during the intensive phases of the experiment, when ship-board radar measurements and aircraft over-flights take place, to enhance the spatial coverage of wave observations. The free-floating buoys will be deployed upwind of FLIP, then allowed to drift for several hours (while being monitored), and retrieved downwind off FLIP. Numerous ship-board buoy deployments will be conducted during the 4-week-long experiment in concert with other ship-board measurements and aircraft over-flights. Together, the moored and free-floating buoys will form an array for observing wave group evolution over a distance of approximately 15 km. The deployment of the free-floating buoys can be adapted to the attendant weather (wind/swell) conditions, the configuration of ship-board and airborne radar systems, and data assimilation strategies employed in the numerical modeling efforts.

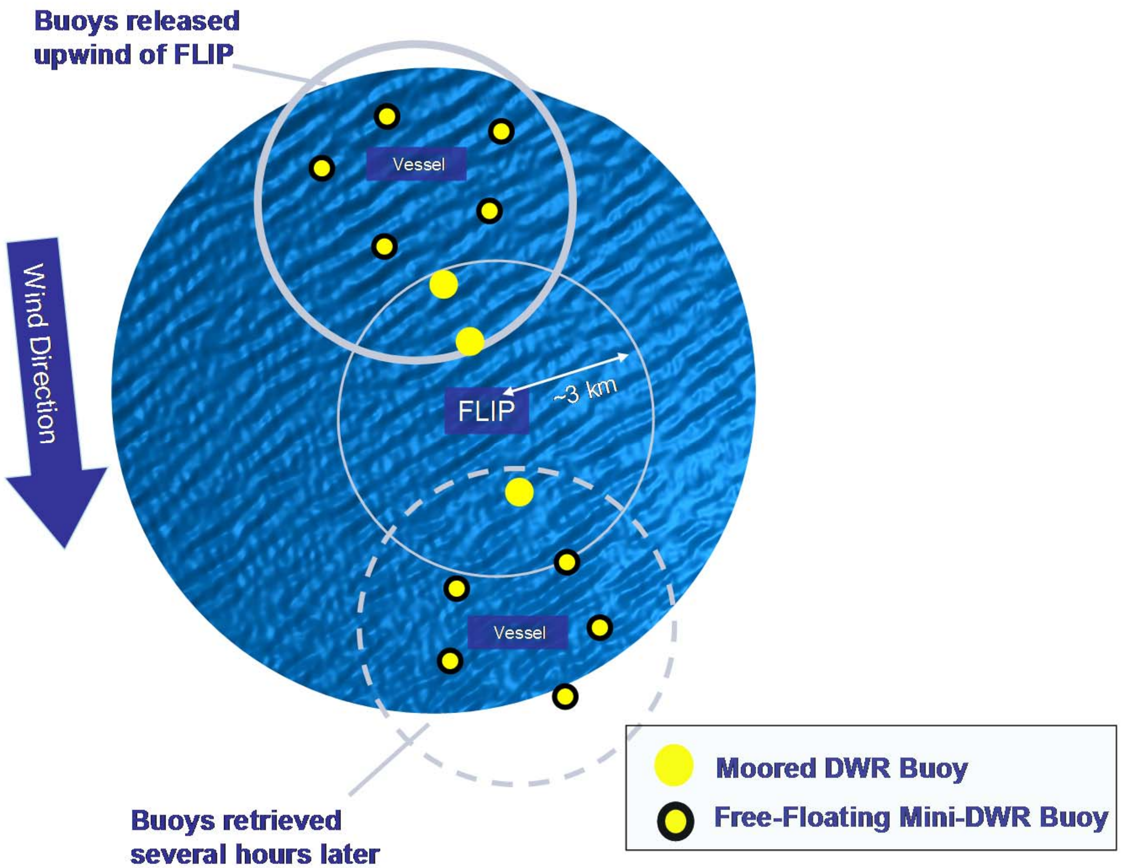

Figure 2. Sketch of a possible experiment configuration. Three moored directional waverider (DWR) buoys span the footprint of FLIP-based radar systems. Five free floating mini-DWR buoys will be deployed from a research vessel equipped with ship-board radar systems (footprint indicated in figure). The vessel will remain near the free-floating buoys and keep them in the radar footprint (dashed circles) as they drift downwind. After several hours the buoys will be retrieved and redeployed upwind of FLIP.

RESULTS

It is well known that the weak nonlinearity of ocean surface waves can cause deviations from Gaussian statistics and an increase in likelihood of extreme wave heights. However, numerical simulations show that nonlinear wave-wave interactions in freely evolving random wave fields cause a directional broadening that stabilizes the wave field toward a near-Gaussian state, thus suppressing the development of 'freak' waves. On the other hand, when waves propagate through a sudden medium variation such as a spatially varying current or a seafloor topographic feature, this equilibrium may be upset and instabilities may develop, resulting in non-Gaussian statistics and an increased likelihood of extreme wave events. To investigate this hypothesis, we developed a numerical model that incorporates the combined effects of cubic wave nonlinearity and refraction induced by a weak lateral medium variation. Results of an example simulation of waves propagating into a weak opposing shear current are shown in Figures 3 and 4. The narrow-band 10 s period swell waves are initially stable

maintaining a near-zero surface kurtosis. Refractive focusing by the relatively weak current (maximum speed 1 m/s) causes an amplification of the waves and a directional broadening expected from geometrical optics (Figure 3). This linear change in wave conditions occurs rapidly enough to cause a Benjamin-Feir type instability evident in a sharp increase in kurtosis. The maximum kurtosis (indicative of increased likelihood of extreme wave occurrences) develops a few wavelengths behind the refractive focal point, after which the kurtosis gradually relaxes back to zero indicating a return to a Gaussian sea state. Example simulated time series of the initial undisturbed wave field (Figure 4, left panel) and the unstable wave field at the location of maximum kurtosis (right panel) show transformation from normal Gaussian wave groups to a more irregular pattern with occasional much larger waves.

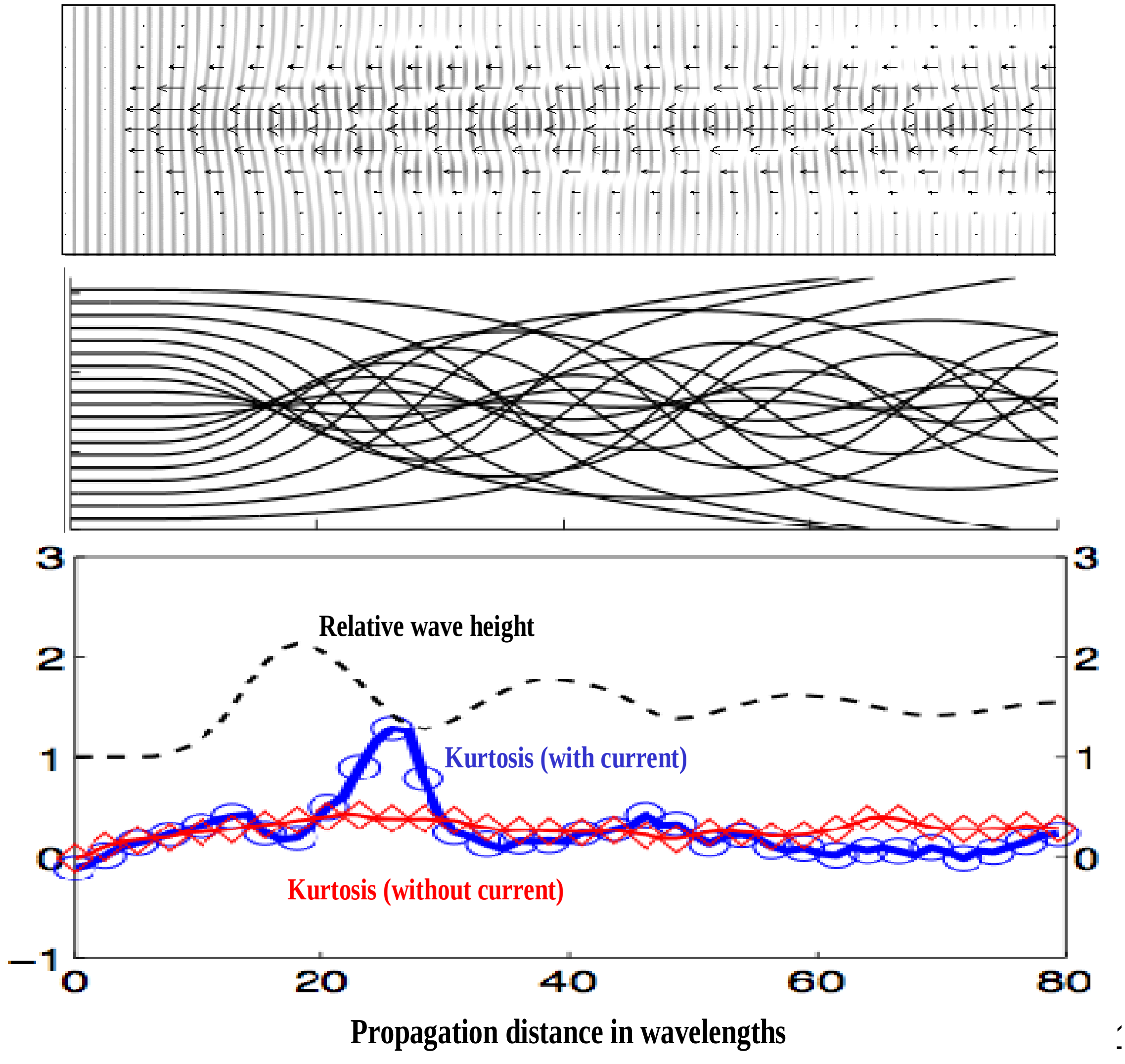

Figure 3. Simulation of swell propagating into a weak opposing shear current. Top panel: plan view of wave field (crests) superimposed on current vectors (maximum current 1 m/s). Middle panel: ray trajectories for the spectral peak (0.1 Hz) component opposing the current. Note the refractive caustics along the current axis. Bottom panel: evolution of relative wave height (dashed black line) and kurtosis (blue circles) along the current axis. Also shown is the kurtosis evolution without the ambient current (red diamonds). (from Janssen and Herbers, 2008)

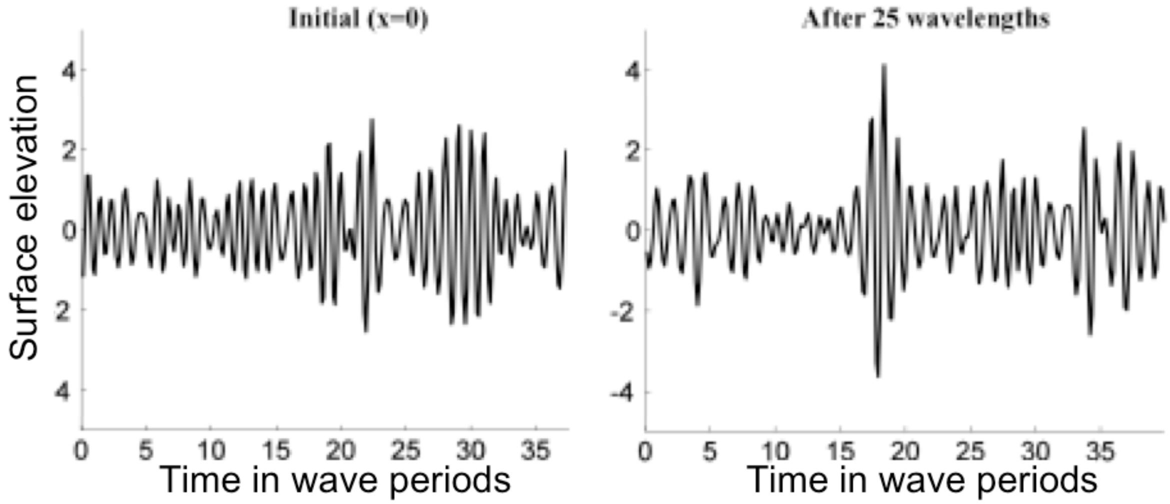

Figure 4. Example surface elevation time series of the simulation of swell propagating into an opposing current (Figure 3). Left panel: the initial wave field at x=0. Right panel: after 25 wavelengths large waves develop in the lee of the refractive focal point. The time series are normalized by the standard deviation of the surface excursions. (from Janssen and Herbers, 2008)

These results confirm the hypothesis that refractive focusing of wave energy can cause a random wave field to become unstable and develop strongly non-Gaussian statistics with an increased likelihood of extreme waves. Computations of waves propagating over a sea mount produce similar results with large kurtosis values on the leeward side of the shoal (Janssen and Herbers, 2008).

IMPACT/APPLICATIONS

This project will yield an improved understanding of ocean surface wave dynamics in deep water and a comprehensive verification of numerical models and radar remote sensing techniques in natural broad-band sea states. These results are critical in the future development of a system for routine monitoring of the wave resolved sea surface around a vessel.

RELATED PROJECTS

We are investigating ocean wave dynamics in shallow water environments in the ONR Coastal Geosciences Projects: Wave-Mud Interactions and the Seafloor Ripples DRI. While the focus in these projects is on the interactions of ocean waves with the seafloor, the numerical modeling approaches and measurement techniques are similar. In addition to these synergies, the combined deep- and shallow-water efforts will provide valuable insight in the role of finite-depth effects in nonlinear wave dynamics, and the associated wave group properties and extreme wave statistics.

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PUBLICATIONS

Janssen T. T., and T. H. C. Herbers, Nonlinear wave statistics in a focal zone, *J. Phys. Oceanogr*, 2008. [submitted, refereed]